

Neutrino Masses and Leptogenesis from R Parity Violation

Ernest Ma

*Department of Physics
University of California
Riverside, CA 92521, USA*

Abstract

In R parity violating supersymmetry (conserving baryon number B but violating lepton number L), Majorana neutrino masses may arise at tree level, in one loop, and in two loops. The L violating interactions work together with the $B + L$ violating electroweak sphalerons to erase any preexisting B or L asymmetry of the Universe. To have successful leptogenesis nevertheless, a specific scenario is proposed. [1]

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1 Introduction

In the minimal Standard Model, leptons appear under $SU(3)_C \times SU(2)_L \times U(1)_Y$ as left-handed doublets $(\nu_i, l_i)_L \sim (1, 2, -1/2)$ and right-handed singlets $l_{iR} \sim (1, 1, -1)$, but there is no $\nu_{iR} \sim (1, 1, 0)$. Hence any $m_\nu \neq 0$ must necessarily come from the effective operator [2]

$$\frac{1}{\Lambda}(\nu_i\phi^0 - l_i\phi^+)(\nu_j\phi^0 - l_j\phi^+), \quad (1)$$

where $(\phi^+, \phi^0) \sim (1, 2, 1/2)$ is the usual Higgs scalar doublet. The structure of this operator clearly shows that *any* Majorana neutrino mass is *seesaw* in character, i.e. of the form v^2 divided by an effective heavy mass, where v is the vacuum expectation value (VEV) of ϕ^0 as the electroweak gauge symmetry $SU(2)_L \times U(1)_Y$ is broken down to $U(1)_Q$. Different models of neutrino mass are merely different realizations [3] of this operator.

2 Canonical Seesaw and Higgs Triplet Mechanisms for Neutrino Masses and Leptogenesis

The most famous mechanism for getting a small m_ν is the canonical seesaw [4] where a heavy singlet neutral fermion N is inserted between the two factors of Eq. (1) with a large Majorana mass m_N . Hence one may read off the neutrino mass as $m_\nu = f_i f_j v^2 / m_N$. An equally *simple* and *natural* mechanism [5] is to realize Eq. (1) with a heavy Higgs scalar triplet (ξ^{++}, ξ^+, ξ^0) with couplings f_{ij} to 2 lepton doublets and μ to 2 Higgs doublets. The neutrino mass matrix is then given by $2f_{ij}\mu v^2/m_\xi^2$. This may be interpreted also as $\nu_i\nu_j$ coupling to the VEV of ξ^0 , which shows clearly the important point that it is possible as well as natural for $\langle \xi^0 \rangle$ to be very much less than m_ξ .

Both of these two simple neutrino-mass mechanisms are also ideal for leptogenesis. The heavy singlet neutral fermion N may decay into $e^-\phi^+$ with lepton number $L = 1$ or $e^+\phi^-$

with $L = -1$. With 2 or more N 's, the one-loop corrections (involving both vertex and self-energy graphs) allow for CP violation in their interference with the tree graph, and may generate [6] a lepton asymmetry of the Universe if the decay of the lightest N occurs out of thermal equilibrium as the Universe expands and cools. The heavy ξ^{++} may decay into e^+e^+ with $L = -2$ or $\phi^+\phi^+$ with $L = 0$. Again, with 2 or more ξ 's, the one-loop (self-energy only) graph allows for CP violation and creates [5] a lepton asymmetry, i.e.

$$|A + iB|^2 - |A^* + iB^*|^2 = 4\text{Im}(AB^*). \quad (2)$$

3 R Parity Violating Supersymmetry and Neutrino Masses

I now come to my main topic which is the generation of neutrino masses through R parity violation in supersymmetry [7]. The well-known superfield content of the Minimal Supersymmetric Standard Model (MSSM) is given by

$$Q_i = (u_i, d_i)_L \sim (3, 2, 1/6), \quad u_i^c \sim (3^*, 1, -2/3), \quad d_i^c \sim (3^*, 1, 1/3), \quad (3)$$

$$L_i = (\nu_i, l_i)_L \sim (1, 2, -1/2), \quad l_i^c \sim (1, 1, 1); \quad (4)$$

$$H_1 = (h_1^0, h_1^-) \sim (1, 2, -1/2), \quad H_2 = (h_2^+, h_2^0) \sim (1, 2, 1/2). \quad (5)$$

Given the above transformations under the standard $SU(3) \times SU(2) \times U(1)$ gauge group, the corresponding superpotential should contain in general all gauge-invariant bilinear and trilinear combinations of the superfields. However, to forbid the violation of both baryon number B and lepton number L , each particle is usually assigned a discrete R parity

$$R \equiv (-1)^{3B+L+2j}, \quad (6)$$

which is assumed to be conserved by the allowed interactions. Hence the MSSM superpotential has only the terms $H_1 H_2$, $H_1 L_i l_j^c$, $H_1 Q_i d_j^c$, and $H_2 Q_i u_j^c$. Since the superfield $\nu_i^c \sim (1, 1, 0)$

is absent, $m_\nu = 0$ in the MSSM as in the minimal Standard Model. Neutrino oscillations [8, 9, 10] are thus unexplained.

Phenomenologically, it makes sense to require only B conservation (to make sure that the proton is stable), but to allow L violation (hence R parity violation) so that the additional terms $L_i H_2$, $L_i L_j l_k^c$, and $L_i Q_j d_k^c$ may occur. Note that they all have $\Delta L = 1$. Neutrino masses are now possible [11] with Eq. (1) realized in at least 3 ways.

The first way is to use the bilinear terms

$$-\mu H_1 H_2 + \epsilon_i L_i H_2, \quad (7)$$

from which a 7×7 neutralino-neutrino mass matrix is obtained:

$$\mathcal{M}_\mathcal{N} = \begin{bmatrix} M_1 & 0 & -g_1 v_1 & g_1 v_2 & -g_1 u_i \\ 0 & M_2 & g_2 v_1 & -g_2 v_2 & g_2 u_i \\ -g_1 v_1 & g_2 v_1 & 0 & -\mu & 0 \\ g_1 v_2 & -g_2 v_2 & -\mu & 0 & \epsilon_i \\ -g_1 u_i & g_2 u_i & 0 & \epsilon_i & 0 \end{bmatrix}, \quad (8)$$

where $v_{1,2} = \langle h_{1,2}^0 \rangle / 2$ and $u_i = \langle \tilde{\nu}_i \rangle / 2$, with $i = e, \mu, \tau$. Note first that both ϵ_i and u_i are nonzero in general. Note also that even if u_i / ϵ_i is not the same for all i , only one linear combination of the three neutrinos gets a tree-level mass. In terms of the effective operator of Eq. (1), this is a tree-level realization with ν_i mixing with \tilde{h}_1^0 (through ϵ_i / μ) which then connects with $\langle h_1^0 \rangle$ and a linear combination of the $SU(2)_Y$ and $U(1)_Y$ gauginos. The latter has a soft supersymmetry breaking Majorana mass and acts just like N in generating a small m_ν . Specifically,

$$m_{\nu_i} = -\frac{(c^2 M_1 + s^2 M_2) g_1^2 (v_1 \epsilon_i + \mu u_i)^2}{s^2 M_1 M_2 \mu^2 - 2 g_1^2 v_1 v_2 \mu (c^2 M_1 + s^2 M_2)}, \quad (9)$$

where $s \equiv \sin \theta_W$ and $c \equiv \cos \theta_W$.

The second way is to use the trilinear terms, from which neutrino masses are obtained [11] as one-loop radiative corrections. Note that these occur as the result of supersymmetry

breaking and are also suppressed by m_d^2 or m_l^2 . A typical graph connects ν_i and ν_j through the intermediate states (b, \tilde{b}^c) and (b^c, \tilde{b}) which are linked by 2 $\langle h_1^0 \rangle$'s, as required by Eq. (1).

Here

$$m_\nu \sim \frac{3\lambda'^2}{16\pi^2} \frac{Am_b^2}{m_{\tilde{b}}^2}. \quad (10)$$

For $m_\nu \sim 0.05$ eV, this implies $\lambda' > 10^{-4}$ for $m_b^2/A > 100$ GeV.

The third way is to recognize the fact that the sneutrino $\tilde{\nu}$ may have a “Majorana” mass term, i.e. $m^2\tilde{\nu}\tilde{\nu} + h.c.$, in addition to the usual “Dirac” mass term, i.e. $M^2\tilde{\nu}^*\tilde{\nu}$. This leads inevitably [12] to $m_\nu \neq 0$, but the effect occurs in two loops and is usually negligible. An interesting exception is in the case of the specific leptogenesis scenario [1] to be discussed below.

4 R Parity Violating Supersymmetry and Leptogenesis

As noted earlier, the R parity violating interactions have $\Delta L = 1$. Furthermore, the particles involved have masses at most equal to the supersymmetry breaking scale, i.e. a few TeV. This means that their L violation together with the $B+L$ violation by sphalerons [13] would erase any primordial B or L asymmetry of the Universe [14]. To avoid such a possibility, one may reduce the relevant Yukawa couplings to less than about 10^{-7} , but a typical minimum value of 10^{-4} (see previous section) is required for realistic neutrino masses. Hence the existence of the present baryon asymmetry of the Universe is unexplained if neutrino masses originate from these $\Delta L = 1$ interactions. This is a generic problem of all models of radiative neutrino masses where the L violation can be traced to interactions occurring at energies below 10^{13} GeV or so.

Once the notion of R parity violation is introduced, there are many new terms to be added in the Lagrangian. Some may be responsible for realistic neutrino masses and may even

participate in the erasure of any primordial B or L asymmetry of the Universe, but others may be able to produce a lepton asymmetry [15] on their own which then gets converted into the present observed baryon asymmetry of the Universe through the sphalerons.

Consider the usual 4×4 neutralino mass matrix in the $(\tilde{B}, \tilde{W}_3, \tilde{h}_1^0, \tilde{h}_2^0)$ basis:

$$\mathcal{M}_{\mathcal{N}} = \begin{bmatrix} M_1 & 0 & -sm_3 & sm_4 \\ 0 & M_2 & cm_3 & -cm_4 \\ -sm_3 & cm_3 & 0 & -\mu \\ sm_4 & -cm_4 & -\mu & 0 \end{bmatrix}, \quad (11)$$

where $m_3 = M_Z \cos \beta$, $m_4 = M_Z \sin \beta$, and $\tan \beta = v_2/v_1$. The above assumes that ϵ_i and u_i are negligible in Eq. (8), which is a good approximation because neutrino masses are so small. I now choose the special case of

$$m_3, m_4 \ll M_2 < M_1 < \mu. \quad (12)$$

As a result, the two higgsinos $\tilde{h}_{1,2}^0$ form a heavy Dirac particle of mass μ and the other two less heavy Majorana fermion mass eigenstates are

$$\tilde{B}' \simeq \tilde{B} + \frac{sc\delta r_1}{M_1 - M_2} \tilde{W}_3 + \dots, \quad (13)$$

$$\tilde{W}_3' \simeq \tilde{W}_3 - \frac{sc\delta r_2}{M_1 - M_2} \tilde{B} + \dots, \quad (14)$$

where $\delta = M_Z^2 \sin 2\beta / \mu$, and

$$r_{1,2} = \frac{1 + M_{1,2}/\mu \sin 2\beta}{1 - M_{1,2}^2/\mu^2}. \quad (15)$$

I now observe that whereas \tilde{B} couples to both $\bar{l}_L \tilde{l}_L$ and $\bar{l}_L^c \tilde{l}_L^c$, \tilde{W}_3 couples only to $\bar{l}_L \tilde{l}_L$ because l_L^c is trivial under $SU(2)_L$. On the other hand, R parity violation implies that there is $\tilde{l}_L - h^-$ mixing as well as $\tilde{l}_L^c - h^+$ mixing. Therefore, both \tilde{B}' and \tilde{W}_3' decay into $l^\pm h^\mp$ and may be the seeds of a lepton asymmetry in such a scenario.

Let the $\tilde{l}_L - h^-$ mixing be very small (which is a consistent assumption for realistic neutrino masses from bilinear R parity violation). Then \tilde{W}_3' decays only through its \tilde{B}

component. Hence the decay rate of the LSP (Lightest Supersymmetric Particle), i.e. \tilde{W}'_3 , is very much suppressed, first by δ and then by the $\tilde{l}_L^c - h^+$ mixing which will be denoted by ξ . This construction is aimed at satisfying the out-of-equilibrium condition:

$$\Gamma(\tilde{W}'_3 \rightarrow l^\pm h^\mp) < H = 1.7\sqrt{g_*}(T^2/M_{Pl}) \quad (16)$$

at the temperature $T \sim M_2$, where H is the Hubble expansion rate of the Universe with g_* the effective number of massless degrees of freedom and M_{Pl} the Planck mass. This implies

$$\left(\frac{\xi|\delta|r_2}{M_1 - M_2}\right)^2 \frac{1}{M_2} < 1.9 \times 10^{-14} \text{GeV}^{-1}, \quad (17)$$

where $g_* = 10^2$ and $M_{Pl} = 10^{18} \text{ GeV}$.

The lepton asymmetry generated from the decay of \tilde{W}'_3 has both vertex and self-energy loop contributions from the insertion of \tilde{B}' . However, the coupling of \tilde{B}' to $l^\pm h^\mp$ is suppressed only by ξ and not by δ , thus a realistic asymmetry may be established if ξ is not too small. Let $x \equiv M_2^2/M_1^2$, then the decay asymmetry of \tilde{W}'_3 is given by

$$\epsilon = \frac{\alpha\xi^2}{2\cos^2\theta_W} \frac{\text{Im}\delta^2}{|\delta|^2} \frac{\sqrt{x}g(x)}{1-x}, \quad (18)$$

where

$$g(x) = 1 + \frac{2(1-x)}{x} \left[\left(\frac{1+x}{x} \right) \ln(1+x) - 1 \right], \quad (19)$$

and $\text{Im}\delta$ comes from the relative phase between M_1 and M_2 .

At $T < M_2$, a lepton asymmetry may start to appear, but there are also reactions which destroy it: (I) recombination (inverse decay), i.e.

$$l^\pm + h^\mp \rightarrow \tilde{W}'_3 \text{ (weak)}, \quad l^\pm + h^\mp \rightarrow \tilde{B}' \text{ (strong)}; \quad (20)$$

(II) scattering, i.e. $l^\pm + h^\mp \rightarrow l^\mp + h^\pm$ with \tilde{W}'_3 (negligible) and \tilde{B}' (weak) as intermediate states; and (III) annihilation, i.e. $\tilde{W} + \tilde{W} \rightarrow W + W$ which is L and R conserving (weak). The Boltzmann equations must then be numerically solved to see if a lepton asymmetry

($\epsilon_L = n_B/g_* n_\gamma$) of order 10^{-10} can be generated for a given set of input parameters. The choice of values for M_1 and M_2 is crucial for this purpose, because the inverse decay of \tilde{B}' is capable of depleting ϵ_L by several orders of magnitude. For example, if $M_1 = 3$ TeV and $M_2 = 2$ TeV, then $\epsilon_L \sim 10^{-14}$.

Two scenarios which work are [1]

$$\begin{aligned} \text{(A)} \quad & M_2 = 3.5 \text{ TeV}, \quad M_1 = 6 \text{ TeV}, \quad \mu = 10 \text{ TeV}, \\ & \xi = 5 \times 10^{-3}, \quad \sin 2\beta = 0.10, \quad m_h = 200 \text{ GeV}; \end{aligned} \tag{21}$$

$$\begin{aligned} \text{(B)} \quad & M_2 = 2 \text{ TeV}, \quad M_1 = 5 \text{ TeV}, \quad \mu = 7.5 \text{ TeV}, \\ & \xi = 5 \times 10^{-3}, \quad \sin 2\beta = 0.05, \quad m_h = 200 \text{ GeV}. \end{aligned} \tag{22}$$

Hence realistic leptogenesis is possible if $\xi \sim 10^{-3}$ can be obtained. This is actually not so easy because the origin of $\tilde{l}_L^c - h^+$ mixing in R parity violation is usually the term $H_1 \tilde{L} \tilde{l}^c$, which is very small because $\langle \tilde{\nu} \rangle$ has to be very small. To obtain $\xi \sim 10^{-3}$, it is necessary to add the nonholomorphic [16] term $H_2^\dagger H_1 \tilde{l}^c$ which is generally unconstrained. In the presence of this new term, the sneutrino $\tilde{\nu}$ also gets a ‘‘Majorana’’ mass of order 100 MeV, which then allows m_ν to be of order 10^{-3} eV in 2 loops.

5 Conclusion

- In supersymmetry with L violation (hence R parity violation), realistic neutrino masses are obtained at 0, 1, and 2 loops.

- Successful leptogenesis is possible in a specific scenario:

- (1) LSP is mostly \tilde{W}_3 ,
- (2) gaugino masses M_1 and M_2 have a relative phase,
- (3) $\tilde{l}_L - h^-$ mixing is negligible,

(4) $\tilde{l}_R - h^-$ mixing is $\mathcal{O}(10^{-3})$ from the nonholomorphic $H_2^\dagger H_1 \tilde{l}^c$ term.

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References

- [1] T. Hambye, E. Ma, and U. Sarkar, Phys. Rev. **D62**, 015010 (2000); hep-ph/0006173 (Nucl. Phys. **B**, in press).
- [2] S. Weinberg, Phys. Rev. Lett. **43**, 1566 (1979).
- [3] E. Ma, Phys. Rev. Lett. **81**, 1171 (1998).
- [4] M. Gell-Mann, P. Ramond, and R. Slansky, in *Supergravity*, edited by P. van Nieuwenhuizen and D. Z. Freedman (North-Holland, Amsterdam, 1979), p. 315; T. Yanagida, in *Proceedings of the Workshop on the Unified Theory and the Baryon Number in the Universe*, edited by O. Sawada and A. Sugamoto (KEK Report No. 79-18, Tsukuba, Japan, 1979), p. 95; R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **44**, 912 (1980).
- [5] E. Ma and U. Sarkar, Phys. Rev. Lett. **80**, 5716 (1998); E. Ma, M. Raidal, and U. Sarkar, hep-ph/0006046.
- [6] M. Fukugita and T. Yanagida, Phys. Lett. **174B**, 45 (1986).
- [7] L. Hall and M. Suzuki, Nucl. Phys. **B231**, 419 (1984).
- [8] Y. Fukuda *et al.*, Phys. Lett. **B433**, 9 (1998); **B436**, 33 (1998); Phys. Rev. Lett. **81**, 1562 (1998); **82**, 2644 (1999).

- [9] R. Davis, Prog. Part. Nucl. Phys. **32**, 13 (1994); Y. Fukuda *et al.*, Phys. Rev. Lett. **77**, 1683 (1996); **81**, 1158 (1998); **82**, 1810, 2430 (1999); P. Anselmann *et al.*, Phys. Lett. **B357**, 237 (1995); Erratum: **B361**, 235 (1996); J. N. Abdurashitov *et al.*, Phys. Lett. **B328**, 234 (1994); Phys. Rev. Lett. **83**, 4686 (1999).
- [10] C. Athanassopoulos *et al.*, Phys. Rev. Lett. **75**, 2650 (1995); **77**, 3082 (1996); **81**, 1774 (1998).
- [11] R. Hempfling, Nucl. Phys. **B478**, 3 (1996); F. M. Borzumati, Y. Grossman, E. Nardi, and Y. Nir, Phys. Lett. **B384**, 123 (1996); H.-P. Nilles and N. Polonsky, Nucl. Phys. **B484**, 33 (1997); E. Nardi, Phys. Rev. **D55**, 5772 (1997); M. A. Diaz, J. C. Romao, and J. W. F. Valle, Nucl. Phys. **B524**, 23 (1998); M. Drees, S. Pakvasa, X. Tata, and T. ter Veldhuis, Phys. Rev. **D57**, R5335 (1998); B. Mukhopadhyaya, S. Roy, and F. Vissani, Phys. Lett. **B443**, 191 (1998); E. J. Chun, S. K. Kang, and C. W. Kim, Nucl. Phys. **B544**, 89 (1999); R. Adhikari and G. Omanovic, Phys. Rev. **D59**, 073003 (1999); O. C. W. Kong, Mod. Phys. Lett. **A14**, 903 (1999); S. Rakshit, G. Bhattacharyya, and A. Raychaudhuri, Phys. Rev. **D59**, 091701 (1999); K. Choi, E. J. Chun, and K. Hwang, Phys. Rev. **D60**, 031301 (1999); S. Y. Choi, E. J. Chun, S. K. Kang, and J. S. Lee, Phys. Rev. **D60**, 075002 (1999); L. Clavelli and P. H. Frampton, hep-ph/9811326; D. E. Kaplan and A. E. Nelson, J. High Energy Phys. **0001**, 033 (2000); A. S. Joshipura and S. Vempati, Phys. Rev. **D60**, 111303 (1999); Y. Grossman and H. E. Haber, hep-ph/9906310; G. Bhattacharyya, H.-V. Klapdor-Kleingrothaus, and H. Pas, Phys. Lett. **B463**, 77 (1999); A. Abada and M. Losada, hep-ph/9908352; O. Haug, J. D. Vergados, A. Faessler, and S. Kovalenko, Nucl. Phys. **B565**, 38 (2000); J. C. Romao, M. A. Diaz, M. Hirsch, W. Porod, and J. W. F. Valle, Phys. Rev. **D61**, 071703 (2000); E. J. Chun and S. K. Kang, Phys. Rev. **D61**, 075012 (2000); F. Takayama and M. Yamaguchi, Phys. Lett. **B476**, 116 (2000); C.-H. Chang and T.-F. Feng, Eur. Phys. J. **C12**, 137 (2000); O. C. W. Kong, hep-ph/0004107; M. Hirsch, M. A. Diaz, W. Porod, J. C. Romao, and J. W. F. Valle, hep-ph/0004115.
- [12] M. Hirsch, H.-V. Klapdor-Kleingrothaus, and S. Kovalenko, Phys. Lett. **B398**, 311 (1997).
- [13] V. A. Kuzmin, V. A. Rubakov, and M. E. Shaposhnikov, Phys. Lett. **155B**, 36 (1985).
- [14] B. A. Campbell, S. Davidson, J. E. Ellis, and K. Olive, Phys. Lett. **B256**, 457 (1991); W. Fischler, G. F. Giudice, R. G. Leigh, and S. Paban, Phys. Lett. **B258**, 45 (1991);

- H. Dreiner and G. G. Ross, Nucl. Phys. **B410**, 188 (1993); J. M. Cline, K. Kainulainen, and K. A. Olive, Phys. Rev. **D49**, 6394 (1994); E. Ma, M. Raidal, and U. Sarkar, Phys. Lett. **B460**, 359 (1999).
- [15] M. Flanz, E. A. Paschos, and U. Sarkar, Phys. Lett. **B345**, 248 (1995); Erratum: **B382**, 447 (1996); M. Flanz, E. A. Paschos, U. Sarkar, and J. Weiss, Phys. Lett. **B389**, 693 (1996); W. Buchmuller and M. Plumacher, Phys. Lett. **B389**, 73 (1996); **B431**, 354 (1998); L. Covi, E. Roulet, and F. Vissani, Phys. Lett. **B384**, 169 (1996); L. Covi and E. Roulet, Phys. Lett. **B399**, 113 (1997); E. Roulet, L. Covi, and F. Vissani, Phys. Lett. **B424**, 101 (1998); A. Pilaftsis, Phys. Rev. **D56**, 5431 (1997); Int. J. Mod. Phys. **A14**, 1811 (1999); M. Flanz and E. A. Paschos, Phys. Rev. **D58**, 113009 (1998); J.-M. Frere, F.-S. Ling, M. H. G. Tytgat, and V. Van Elewyck, Phys. Rev. **D60**, 016005 (1999); R. Rangarajan and H. Mishra, Phys. Rev. **D61**, 043509 (2000); R. Barbieri, P. Creminelli, A. Strumia, and N. Tetradis, Nucl. Phys. **B575**, 61 (2000); G. Mangano and G. Miele, hep-ph/9912471; O. Lalakulich, E. A. Paschos, and M. Flanz, Phys. Rev. **D62**, 053006 (2000).
- [16] L. J. Hall and L. Randall, Phys. Rev. Lett. **65**, 2939 (1990); F. Borzumati, G. R. Farrar, N. Polonsky, and S. Thomas, Nucl. Phys. **B555**, 53 (1999).